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Research and Application of EMUs Braking System Control Logic Based on MBSE

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Abstract: As Model-Based Systems Engineering (MBSE) was applied to the Electric Multiple Unit (EMU) braking system control logic, a preliminary exploration was conducted for bullet train braking system control logic research using an MBSE practice framework. The framework mainly includes the requirement analysis phase, functional analysis phase, and design phase. Systems Modeling Language (SysML) was used as the modeling language, and Cameo Systems Modeler (CSM) was employed as the modeling tool. By integrating the EMU braking system control logic and utilizing a top-down design approach, the implementation of MBSE in the bullet train braking system was analyzed and studied. The results show that, according to the MBSE practice framework, a unified description of the requirement analysis, functional analysis, and design synthesis of the EMU braking system control logic can be achieved. Additionally, the correlation and traceability between models can be established.

Keywords: MBSE; Braking system; Control logic; SysML

1. Introduction

In Traditional Systems Engineering (TSE), a series of documents written in natural language are used to express user requirements, design schemes, analysis reports, and physical models made of real objects. However, TSE documentation has obvious shortcomings. As the system size increases, it becomes challenging to maintain consistency in engineering design. If the latest glossary and vocabulary are not used, it may lead to misunderstandings and inconsistencies [1].

The International Council on Systems Engineering (INCOSE) formally defined Model-Based Systems Engineering (MBSE) in 2007 [4,5]. MBSE addresses the limitations of Traditional Systems Engineering (TSE) in managing complex systems, enhances work efficiency, and reduces costs.

An Electric Multiple Unit (EMU) is a typical complex industrial system, consisting of multiple subsystems with intricate interrelationships. It involves various disciplines, making its design highly complex. Currently, the domestic development of EMUs primarily follows Traditional Systems Engineering (TSE), which poses challenges for the inheritance and reuse of certain subsystem models, as well as for the maintenance and management of development experience, knowledge, and the EMU life cycle.

Based on the principles of Model-Based Systems Engineering (MBSE) and the control logic of the EMU braking system, this paper explores the implementation of MBSE in the braking control logic of EMUs from the perspective of forward design. This research enables a unified description of requirement analysis, functional analysis, and design synthesis for the control logic of the EMU braking system while ensuring correlation and traceability between various models.

2. Practical basis of EMU braking system based on MBSE

2.1. Modeling language

Since the Object Management Group (OMG) endorsed Unified Modeling Language (UML) as a standardized modeling language, UML has been widely adopted in industry, science, and technology. To meet the needs of systems engineering, the International Council on Systems Engineering (INCOSE) and OMG extended and reused UML 2.0, developing a new system modeling language known as Systems Modeling Language (SysML) [3].

SysML defines requirements on the semantic model, structure model, behavior model, and parameter model, to visualize the important aspect of system design and the convenient communication modelers. SysML offers the following advantages over UML 2.0.

Firstly, SysML represents systems engineering semantics better than UML, this approach can reduce software offset in UML, and two new requirements diagrams and parameter diagrams are added.

Secondly, SysML is smaller and easier to learn than UML. SysML gets rid of a lot of unreasonable structure, so the diagram types and overall structure of the whole language are smaller [5]. To sum up, this paper adopts SysML modeling language.

2.2. Modeling tools

Mainstream Model-Based Systems Engineering (MBSE) modeling tools include IBM Rational Rhapsody, Capella, MagicDraw, and M-Design, among others. With the rapid development of various industries worldwide driving MBSE adoption, No Magic’s MBSE products have experienced significant growth. Their products are known for powerful capabilities, good usability, and cost-effective implementation.

The core team at No Magic has been deeply involved in the research and development of Systems Modeling Language (SysML) standards, ensuring that their products naturally conform to these standards. Additionally, No Magic was among the early adopters in realizing SysML-based product implementations.

Based on a summary analysis and insights from foreign rail transit enterprises, this paper adopts the Cameo Systems Modeler (CSM) as the MBSE modeling tool.

2.3. Practical framework

With the gradual development of Model-Based Systems Engineering (MBSE), several MBSE methods have emerged, including the Object-Oriented Systems Engineering Method (OOSEM), the Harmony-SE method, the

Vitech MBSE method, and the Object-Process Methodology (OPM) defined by Dori. This study summarizes these classic methods and formulates an MBSE research framework for the bullet train braking system control logic. The practical implementation is shown in **Figure 1**.

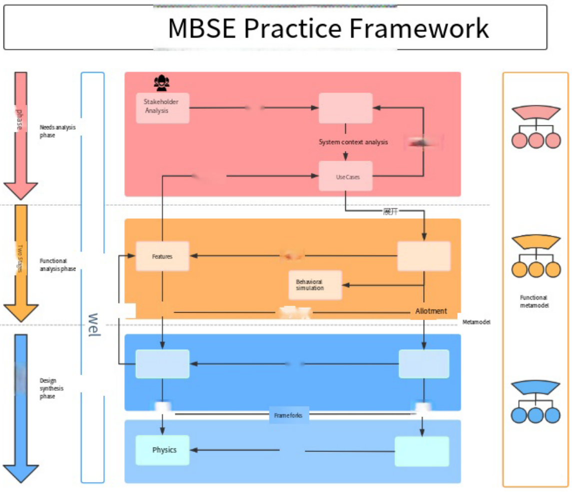


Figure 1. MBSE practice framework

(1) Requirements analysis stage: Identify stakeholder requirements through investigation, discussion, and literature review. Analyze these requirements and use Cameo Systems Modeler (CSM) to create models. This stage generates use case diagrams and a traceability matrix that links use cases to user requirements.

(2) Function analysis stage: Based on the output from the requirements analysis stage, determine the necessary functions to meet system requirements. Use CSM to model and decompose functions for further design.

(3) Integrated design (architecture) stage: Integrate the functional analysis model elements into the system architecture. Decompose functions and assign them to corresponding physical components using CSM. The traceability matrix is used to ensure completeness and verify traceability between use cases.

3. Requirements analysis phase

3.1. Stakeholder analysis

According to ISO/IEC/IEEE 29148:2018, stakeholders include but are not limited to, end-users, developers, trainers, maintainers, customers, operators, and regulators. To identify stakeholders, various methods were used, including customer interviews, market research, stakeholder analysis, elaboration, clustering, and comprehensive assessment. The identified stakeholders are as follows:

(1) All individuals on the train, including passengers and train staff.

(2) Railway operators, including depots, passenger depots, electric depots, and locomotive depots.

(3) EMU braking system suppliers, such as Beijing Zhongheng, Nanjing Haitai, Qishuyan, and Tianyi Shangjia.

(4) Related systems, including the Traction Control Unit (TCU), Train Control and Monitoring System (TCMS), and train operation control system.

(5) Constraints and restrictions, including laws and regulations, industry standards, and environmental conditions such as haze, salt fog, acid rain, coastal humidity, highland sand, snow, and rain.

3.2. Requirements

Requirements analysis is a step-by-step process that involves itemizing requirements. Throughout the entire product lifecycle, requirement traceability must be ensured across various stages. This allows for the timely identification of new requirements, modification of unreasonable demands, and overall design improvement.

Requirement entries are listed according to itemized specifications and exist across multiple layers. Each requirement entry can be edited, modified, associated with other requirements, and status-tracked. The basic elements of a requirement entry include: requirement ID (number), title, and description.

According to ISO/IEC/IEEE 29148:2018, requirement descriptions should be written in natural language. Each statement must include a subject and a verb, describe the subject system, and define the measures or constraints to be considered. The itemized requirements for the braking system are presented in **Table 1**.

Table 1. User requirements

Number ID	Title	Description
R1000	Braking	Applying common braking, including UB emergency brake, EB emergency braking, parking brake, keep the brake, clean all user requirements.
R2000	Air supply	Including the main air compressor control and other user requirements.
R3000	Sanding	Include all user requirements for sanding.
R4000	Skid resistance	Includes non-rotating shaft detection, wheel sliding protection and other user requirements.
R5000	Testing	Includes all user requirements for both a menu-guided brake test and an automatically performed brake test.
R6000	Diagnostics and troubleshooting	Includes all user needs for fault management and diagnosis.
R7000	Assistance	Includes all user needs for emergency traction mode and rescue return.

3.3. Use cases

Use cases focus on specific actions and capture the behavior of the system’s stakeholders in relation to the system. They document different scenarios in which stakeholders interact with the system to achieve their goals. Each use case describes the user’s perspective when interacting with the system, helping to define the system’s intended functionality. Based on the needs of different user groups, requirements are further elaborated into use cases.

3.4. Traceability relationship between use cases and requirements

To meet the requirements of use cases and ensure a more concise model view, the Satisfy traceability matrix is used to describe the traceability relationship between use cases and requirement groups. By utilizing the Satisfy traceability matrix, missed requirements can be identified, and requirements change management can be effectively facilitated.

4. Functional analysis phase

4.1. Functional analysis process

The Functional Breakdown Structure (FBS) of railway trains is defined in EN15380-4 Part 4, which provides guidelines for systematically organizing the functional components of a railway vehicle. Developing a functional breakdown structure requires adherence to key principles that establish a hierarchical framework for defining system functions.

At the highest level, the functional domain or service of the vehicle represents the primary function, which serves as the foundation for all subsequent functions. Supporting this primary function are secondary functions, which contribute directly to its execution. Further decomposition results in Level 3 functions, which support Level 2 functions and consist of multiple Level 4 functions, typically corresponding to specific tasks. At the most detailed level, Level 5 functions encompass activities required to perform Level 4 functions, ensuring a comprehensive and systematic breakdown of the system's functionality.

To enhance the functional decomposition process, existing methodologies have been analyzed alongside the provisions outlined in EN15380-4, particularly those concerning railway vehicle function groups. Based on this analysis, a functional breakdown table for the EMU braking system has been developed. This table offers a structured representation of the braking system's functions, improving clarity in system design and ensuring traceability across different levels of functionality. The details of this breakdown are presented in **Table 2**, which illustrates the hierarchical relationships among the various functions within the braking system.

Table 2. Classification of function groups of EMU braking system

Number ID	Description	Number ID	Description
GCB	Equipped braking system	GCF	Handle braking based on train configuration, braking mode, and braking demand
GCC	Get brake demand	GCG	Apply and relieve the braking force
GCD	Prioritize braking needs and choose a braking mode	GCH	Provides roller skid protection
GCE	Distribution force	GDB	Managing sanding

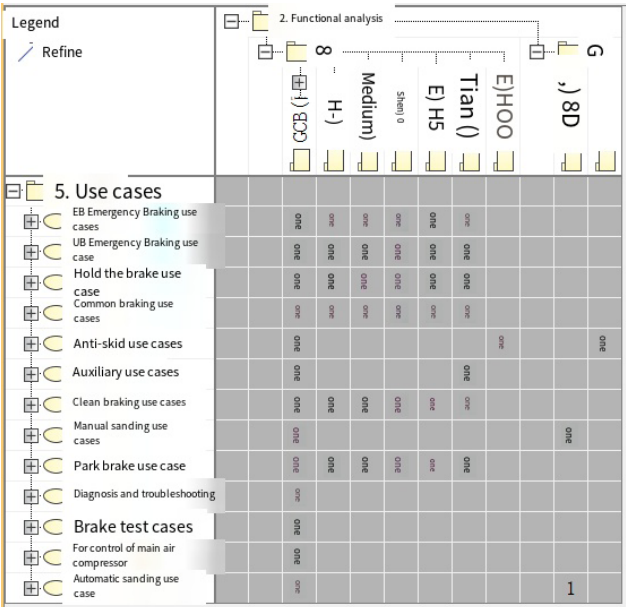
4.2. Functional use case traceability relationship

In order to realize the bidirectional iterative relationship between use cases and functions, the refine traceability matrix is used to describe the traceability relationship between use cases and functions. **Figure 2** shows the traceability matrix diagram between use cases and functions of the braking system.

5. Design synthesis phase

5.1. Architecture modeling

During the demand analysis and functional analysis phases, the braking system is systematically decomposed into several subsystems based on its overall functionality. The determination of these subsystems follows key principles, including identifying the system's role, characteristics, limitations, important data sets, and their sources [10]. Additionally, subsystems are classified according to common functionalities, shared data, and resource requirements. Specific rules governing subsystems are established to ensure logical division, and the identified subsystem features are integrated to form interfaces. Based on this decomposition, the logical



5. Use cases	2. Functional analysis	8	GCB (	H-)	Medium)	Shen) 0	E) H5	Tian ()	E)HOO	G	,) 8D	
EB Emergency Braking use cases			one	one	one	one	one	one				
UB Emergency Braking use case			one	one	one	one	one	one				
Hold the brake use case			one	one	one	one	one	one				
Common braking use cases			one	one	one	one	one	one				
Anti-skid use cases			one						one			one
Auxiliary use cases			one					one				
Clean braking use cases			one	one	one	one	one	one				
Manual sanding use cases			one								one	
Park brake use case			one	one	one	one	one	one				
Diagnosis and troubleshooting			one									
Brake test cases			one									
For control of main air compressor			one									
Automatic sanding use case			one								1	

Figure 2. Cases traceability matrix to function

architecture of the braking system is constructed.

The braking system is divided into several subsystems, including driver braking instruction equipment, straight-through air braking system, wind supply system, foundation braking device, air spring for the risk control system, Brake Pipe (BP) rescue conversion device, and auxiliary equipment. The driver braking instruction equipment is responsible for executing brake commands, while the straight-through air braking system controls air brake functions. The wind supply system ensures adequate airflow for braking operations, and the foundation braking device executes braking commands at the mechanical level. Additionally, the BP rescue conversion device and other auxiliary subsystems support braking operations and contribute to the overall safety and efficiency of the system [11].

5.2. Physical modeling

Based on the analysis of braking system requirements, functions, and logical architecture, the system functions were ultimately assigned to physical components. The braking command transmission relies on the driver's braking command device, which is integrated into the physical architecture. This system primarily includes the brake handle, UB emergency brake button, parking brake application button, parking brake release button, keep brake application button, clean brake button, a double-needle pressure gauge (for displaying the pressure of the main air duct and brake cylinder), and a single-needle pressure gauge (for displaying the pressure of the train tube of the rescue device) [12]. These components are strategically placed in the driver's cab for ease of operation.

In different types of train cars, additional braking components are arranged according to specific requirements. These include the Brake Control Unit (BCU), pneumatic suspension device, parking brake device, wheel anti-skid device, tread cleaner, brake discs, brake calipers, air cylinders, and sanding devices. Each of these elements plays a critical role in ensuring the safe and efficient operation of the EMU braking system under various conditions.

5.3. Architecture function traceability

After the architecture modeling is completed, the correlation and correspondence between the braking system functions and the components of the architecture are established, and the reasonable allocation of functions is realized. The Allocate traceability matrix is used to verify the traceability of functions and architecture [13,14].

6. Conclusion

This paper conducts an in-depth study on the control logic of the bullet train braking system, drawing upon classic Model-Based Systems Engineering (MBSE) methodologies. By exploring the application of the MBSE framework in the control logic of the bullet train braking system, this research systematically examines the requirement analysis, functional analysis, and design stages through comprehensive modeling and analysis. The study ensures traceability between models and validation of system functions, contributing to a structured and efficient design process [15].

Building on the MBSE practice framework for the EMU braking system control logic, this paper further explores the construction of requirement metamodels, function metamodels, architecture metamodels, and physical component metamodels tailored to the professional characteristics of EMU braking systems. This structured approach lays a strong foundation for model integration across subsystems, ensuring consistency and coherence throughout the system development lifecycle.

Disclosure statement

The authors declare no conflict of interest.

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